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Technical Report ARMET-TR-08019

COMPUTER SIMULATION OF A 155-mm PROJECTILE IN A SCAT GUN ASSEMBLY

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September 2008

U.S. ARMY ARMAMENT RESEARCH, DEVELOPMENT AND ENGINEERING CENTER

Munitions Engineering Technology Center

Picatinny Arsenal, New Jersey

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-01-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (*From - To)*
September 2008		

4. TITLE AND SUBTITLE	
COMPUTER SIMULATION OF A 155-mm PROJECTILE IN A SCAT GUN ASSEMBLY	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHORS	5d. PROJECT NUMBER
Kenneth P. Walsh, Ph.D.	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army ARDEC, METC Fuze & Precision Armaments Technology Directorate (AMSRD-AAR-MEF-E) Picatinny Arsenal, NJ 07806-5000	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army ARDEC, ESIC Technical Research Center (AMSRD-AAR-EIK) Picatinny Arsenal, NJ 07806-5000	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S) Technical Report ARMET-TR-08019

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is limited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This report presents the results of a computer simulation of a 45.36 kg 155-mm projectile as it moves through a scat gun assembly using a FORTRAN program. The experimental data was taken from a test performed by the Analysis Engineering and Technical Division at the U.S. Army Armament Research, Development and Engineering Center, Picatinny Arsenal, New Jersey on 7 April 2007 (test CBR5). The data was filtered using an Abaqus Butterworth Filter with a cutoff frequency of 500 Hz because the data plot exhibited "noisy" displays due to the electronic circuitry. The simulation entails aerodynamic deceleration of the projectile and the acceleration/deceleration of the piston inside the assembly in a long tube attached to the gun barrel. The projectile had an entrance velocity of 516 m/s and the shock wave preceding it ruptures the diaphragm. The projectile decelerates as high pressure builds between it and the free piston due to shock-wave propagation. The piston disengages and travels forward scooping water. The waterlog that forms in front of the piston effectively increases the piston's mass and also induces a braking force because of the water friction with the tube wall. The simulation predicts the piston will be decelerated with the piston coming to a rest about 22 m from the back end of the assembly. The computer simulation is based on the closed form formulas, incorporating unsteady one-dimensional fluid dynamics. This report details effects of shockwave induced pressure on the projectile and piston and how accurate the simulations are compared to the actual data plot.

15. SUBJECT TERMS
Projectile pressure Closed form formulas

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBE PERSON Kenneth P. Walsh, Ph.D.
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (Include area code)
U	U	U	SAR	37	(973) 724-6393

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

ACKNOWLEDGMENTS

Appreciation is extended to Jennifer Cordes, Ph.D. who carefully reviewed this report and to Christian Kessler who gave me a number of helpful suggestions during the writing of this report.

CONTENTS

INTRODUCTION

Resent testing was conducted at the U.S. Army Armament Research, Development and Engineering Center (ARDEC), Picatinny Arsenal, New Jersey on a soft recovery system for a 155-mm projectile in an assembly as shown in figure 1 and with numerical details given in figure 2. Sense and destroy armor, such as the 155-mm projectile, have very sensitive components and packaging intrinsic to their design. Projectiles tested to evaluate performance and failure analysis using a soft recovery system is very expensive. As of date, recovery was employed to retrieve the projectile in such a way that the projectile does not exceed damage thresholds. The complexity of the projectile makes it vulnerable to damage during testing and may become too damaged for useful analysis. The use of soft recovery will enhance and enable the verification of launch functionality/performance of the projectile's components, by measuring these variables during the actual testing. This report details a non-numerical closed form model and its predictions for the flow dynamics in the proposed soft recovery work. Not only is there a need for a soft recovery system, but also for a computer program that could accurately predict the projectile's behavior as it is fired through a gun assembly, which could reduce testing costs and speed research and development in ballistics design and implementation.

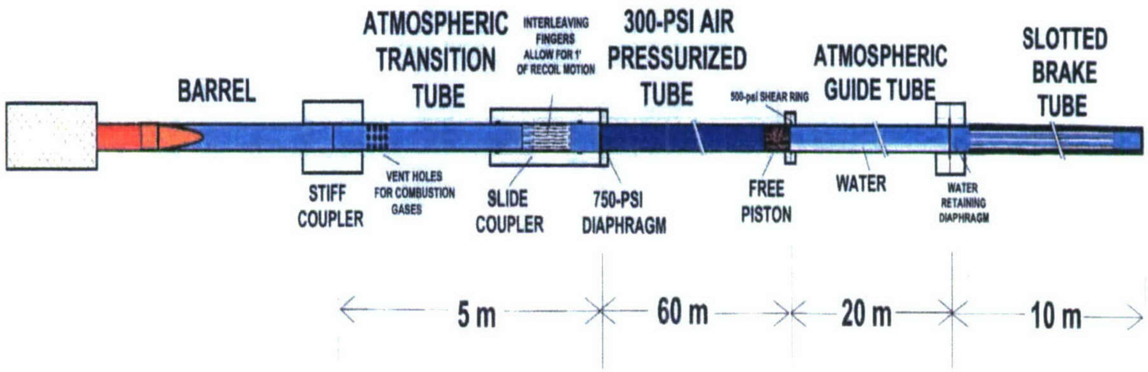
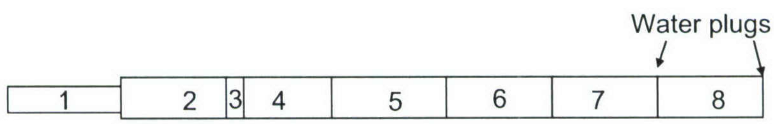


Figure 1
Scat gun assembly (ref. 1)



1. SOLID STEEL CYLINDER PROJECTILE R =.077444 L = .3085
2. HOLLOW STEEL CYLINDER SECTION IR =.07747 OR = .07747 L = 27.9
3. SOLID ALUMINUM DIAPHRAGM IR = 0.0 OR = .1016 L = .002
4. HOLLOW STEEL CYLINDER SECTION IR =.07747 OR =.127 L = 97.6
5. HOLLOW STEEL CYLINDER SECTION IR =.07747 OR=.127 L = .0339
6. SOLID STEEL PISTON IR = 0.0 OR =.077444 L = .0339
7. HOLLOW STEEL CYLINDER SECTION IR =.07747 OR=.127 L = 24.4
8. WATER SECTION IR = 0.0 OR =.0254 L = 24.4

IR - inner radius
OR - outer radius
L = length
MKS units

Figure 2
Scat gun parameters

THEORY

The formulas used in the FORTRAN program (app A) that simulates the scat recovery system were taken from a standard text by Anderson (ref. 2). A shockwave is initially created as the projectile enters the gun tube with a velocity of 516 m/s. The shockwave travels back and forth along the tube where the length of the path in a given direction changes because of the projectile's forward motion. The Mach number of the shockwave changes from its initial value to when the shockwave reflects off the back of the diaphragm and the front of the piston. When the pressure due to the shockwave exceeds the threshold of the diaphragm, the diaphragm bursts and pressure is then exerted upon the back of the piston. Shockwaves are reflected off the back of the piston and the front of the projectile until the piston displacement creates pressure on the water plug until it bursts. The energy expended by the piston in bursting the water plug is equal work done in bursting the water plugs encasing the water section of the scat assembly and pushing the water mass forward. The yield strength of the water plug is used to calculate the energy expended and lost by the piston. The yield strength of the diaphragm and water plugs were both assumed to be equal to 3,447,378 P. The FORTRAN program used in the simulations has two loops: a G loop with and embedded N loop. Both loops have an initial value of one and are incremented by one for each loop. Different Gs represent changing conditions when a barrier is burst. Each N calculates changing variables (i.e., Mach number, shockwave velocity, projectile/piston displacements and velocities) during the simulation when the shockwave completes a circuit in both forward and backward directions as it reflects off of surfaces within the assembly.

Calculation of Initial Mach Number

The non-reflected Mach number can be calculated by knowing the particle velocity in front of the projectile. The particle velocity can be approximated as the initial speed of the projectile V_P. The initial Mach number is calculated as (fig. 3)

$$V_P\gamma = V_S(p_2/p_1 - 1)\sqrt{2\gamma/(\gamma+1)/(p_2/p_1+(\gamma-1)/(\gamma+1))} \tag{1}$$

where $\gamma = c_p/c_v, V_S$ is the shockwave velocity, p_2 is the shockwave pressure in back of the shockwave and on the front of the projectile, and p_1 is the pressure in front of the shockwave and on the back of the diaphragm.

The initial shockwave Mach number is given by

$$M_{INT} = \sqrt{((\gamma+1)/2\gamma)(p_2/p_1-1)+1} \tag{2}$$

Solving equation 1 for p_2/p_1

$$(p_2/p_1)^2 - p_2/p_1\left(2+(V_P/V_S)^2\right)(\gamma+1)/\gamma) - (\gamma-1)/\gamma(V_P/V_S)^2 = 0$$

$$(p_2/p_1)^2 - p_2/p_1\left(2+(V_P/V_S)^2(\gamma+1)/\gamma\right) - (\gamma-1)/\gamma(V_P/V_S)^2 = 0$$

$$a = 1, b = -\left(2+(V_P/V_S)^2(\gamma+1)/\gamma\right), c = -(\gamma-1)/\gamma(V_P/V_S)^2$$

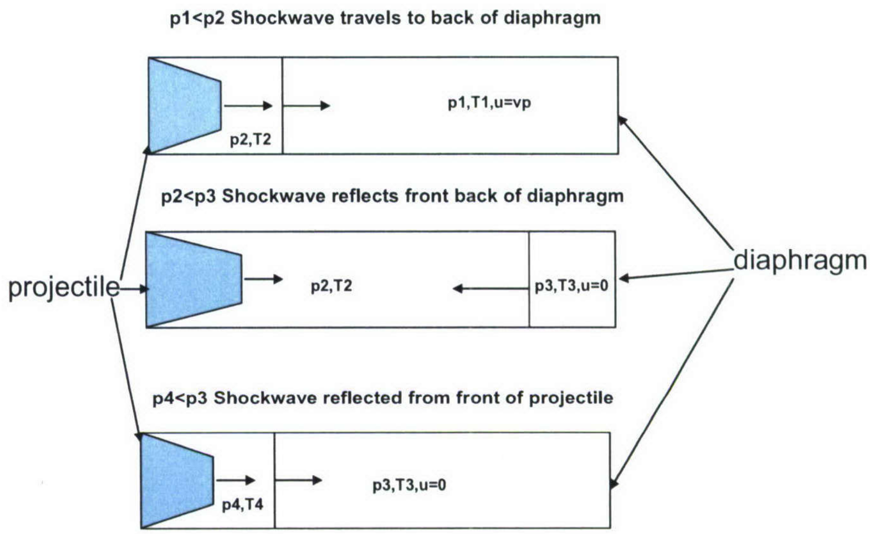


Figure 3
Shockwave propagation and pressure/temperature changes

Mathematically, the solution to this quadratic equation is

$$(p_2 / p_1)\pm = (1/2a)\left(-b \pm \sqrt{b^2 - 4ac}\right) \tag{3}$$

Physically, the only possible solutions occur if

1. $b < 0, \sqrt{b^2 - 4ac} < -b,\ p_2/p_1 = (1/2a)\left(-b - \sqrt{b^2 - 4ac}\right)$

2. $b > 0, -4ac > 0, \sqrt{b^2 - 4ac} > abs(-b),\ p_2 / p_1 = (1/2a)\left(-b + \sqrt{b^2 - 4ac}\right)$

Substitute equation 3 into equation 2 to find initial Mach number.

Calculation of Sound Speed in Region Ahead of Shockwave

Temperatures in regions in front of and in back of the shockwave are function of pressures in those respective regions, which is given generally as

$$T_{2N} = (T_N p_N / p_{2N})(1 + ((\gamma+1)/(\gamma-1)) p_{2N} / p_N)/((\gamma+1)/(\gamma+1) + p_{2N} / p_N) \tag{4}$$

when shockwaves are reflected in the forward direction and

$$T_{2N+1} = (T_{2N} p_{2N} p_{2N+1})(1 + ((\gamma+1)/(\gamma-1)) p_{2N+1} / p_{2N})/((\gamma+1)/(\gamma-1) + p_{2N+1} / p_{2N}) \tag{5}$$

when shockwaves are reflected in the backward direction. Temperatures with the higher subscripts are in regions behind the shockwave.

Substitute the previous relation for p_2 / p_1 from equation 3 to find T_1, T_2, T_3. The initial temperature T_1 in the region where the shockwave is propagating is 300K. The initial sound speed in front of the shockwave can then be calculated from $V_{Si} = \sqrt{\gamma R T_i}$.

Calculation of the Time for Shockwave to Transverse Length of Tube in the Forward Direction

The time $\Delta\tau_N$ upon hitting the back of a barrier the nth time is $\Delta\tau_N = L / V_S$, where L is the initial distance from the projectile to the barrier and V_S is the shockwave velocity.

Calculation of How Far the Projectile Travels within Tube When Shockwave Reflects Off Front of Projectile

The projectile velocity and displacement at any time can be taken from standard formulas in physics. During the time a shockwave is traveling through a medium, the pressure on the front of the projectile is constant and is decelerating it. The nth distance traveled during time $\Delta\tau_n$ in the forward direction

$$\Delta x_N = \int_0^{\Delta\tau_n} (v(x_N) - p_{2N} A t / M_P) dt = v(x_N)(\Delta\tau_N) - p_{2N} A \Delta\tau_N^2 / 2M_P =$$
$$- p_{2N} A (L / V_S)^2 / 2M_P \tag{6}$$

where A is the cross-section area of the projectile, $v(x_N)$ is the initial velocity of the projectile when shockwave is either reflected or created at the surface of the projectile, L is the distance the shockwave has to travel before hitting a barrier, V_S is the shockwave velocity, and M_P is the projectile mass.

Calculation of Time for Reflected Shockwave to Hit Front of Projectile

As the shockwave reflects off the diaphragm, the projectile is still moving forward, but in a decelerating manner. The time the shockwave takes to reflect off the diaphragm and hit the front part of the projectile can easily be shown to be

$$\Delta\tau_{N+1} = (L - \Delta x_N - \Delta x_{N+1}) / M_{BNR} V_S \tag{7}$$

and how far the projectile is displaced during this time interval is

$$\Delta x_{N+1} = \int_0^{\Delta\tau_{N+1}} (v(x_{N+1}) - p_{2N} A t / M_P) dt = v(x_{N+1}) \Delta\tau_{N+1} - p_{2N} A (\Delta\tau_{N+1})^2 / 2M_P$$

$$\Delta x_{N+1} = v(x_{N+1})(L - \Delta x_N - \Delta x_{N+1}) / M_{BNR} V_S - p_{2N} A ((L - \Delta x_N - \Delta x_{N+1}) / M_{BNR} V_S)^2 / 2M_P$$

where $v(x_{N+1})$ is the projectile's velocity when the shockwave is reflected backwards and M_{BNR} is the Mach number calculated from equation 9. Solving Δx_{N+1} involves a quadratic equation.

$$\Delta x_N^2 p_{2N} A_P / \left(2M_P (M_{BNR} V_S)^2\right) + \Delta x_{N+1}\left(1 + v(x_{N+1}) / M_{BNR} V_S - p_{2N} A(L - \Delta x_N) / \left(M_P (M_{BNR} V_S)^2\right) - \right.$$

$$v(x_{N+1})(L - \Delta x_N) / M_{BNR} V_S + p_{2N} A_P / 2M_P ((L - \Delta x_N) / M_{BNR} V_S)^2 = 0$$

a = $p_{2N} A / \left(2M_P (M_{BNR} V_S)^2\right)$

b = $\left(1 + V(x_{N+1}) / M_{BNR} V_S - p_{2N} A(L - \Delta x_N) / \left(M_P (M_{BNR} V_S)^2\right)\right)$

c = $-v(x_{N+1})(L - \Delta x_N) / M_{BNR} V_S + p_{2N} A / \left(2M_P ((L - \Delta x_N) / M_{BNR} V_S)^2\right)$

$$\Delta x_{N+1}(\pm) = \left(-b \pm \sqrt{b^2 - 4ac}\right) / (2a) \tag{8}$$

Physically, the only possible solutions occur if

1. $b < 0, \sqrt{b^2 - 4ac} < -b, p_2 / p_1 = (1/2a)\left(-b - \sqrt{b^2 - 4ac}\right)$

2. $b < 0, -4ac > 0, \sqrt{b^2 - 4ac} > abs(-b), p_2 / p_1 = (1/2a)\left(-b + \sqrt{b^2 - 4ac}\right)$

Knowing Δx_N and Δx_{N-1}, $\Delta \tau_{N+1}$ can be determined from equation 8.

Calculation of the Reflective Mach Number M_R after Shockwave Hits Surface of a Barrier

Upon forward reflection from a surface, the pressure in back of the shockwave becomes p_{2N+1} and in the front of the shockwave p_N as shown in figure 2. For backward reflection from a surface, the pressure in back of the shockwave becomes p_{2N+1} and in the front of the shockwave p_N.

One can now calculate the new reflected Mach number using

$$M_R^2 M_C - M_R - M_C = 0 \tag{9}$$

where $M_C = \left(M_1 / \left(M_1^2 - 1\right)\right)\sqrt{1 + 2(\gamma - 1)\left(M_1^2 - 1\right)\left(\gamma + 1 / M_1^2\right) / (\gamma + 1)^2}$ and M_1 is the old Mach number of the shockwave before reflection and M_R is the new reflected Mach number.

Generally speaking, knowing M_R, the new pressure on the surface of a barrier can be estimated. For backward reflection, $P_{2N+1} = FACTOR * P_{2N}$; for forward reflection $P_{2N} = FACTOR * P_{2N=1}$, where factor is a constant obtainable from standard tables (ref. 3). In both cases, the pressure with the higher subscript is the shockwave pressure on the surface of a barrier nearest to the reflected shockwave.

Calculation Velocity of Piston as a Function of its Displacement

Computer simulation showed that the pressure P of the shockwave on the piston is always much greater than the gas pressure on the front of the piston and the friction forces F during the time the shockwave travels towards or away from the piston. Thus, the acceleration of the piston can be approximated as constant.

$$A_{PS} = [(PA - F] / M_{PS} \tag{10}$$

There are three forces acting on the piston: shock pressure, friction, and pressure from the ideal gas in the chamber between the piston and the water plug. The net force on the piston can be used to calculate the increase in its kinetic energy when the net force on the piston increases its kinetic energy as it is displaced a distance X.

$$M_{PS}V_{PS}^2 / 2 = \int_0^X ((P - vRT)/(L_{PW} - X))A - F)dx = \int_0^X (-vRT/(L_{PW} - X))Adx + \int_0^X (PA - F)dx$$

$$PM_{PS}V_{PS}^2 / 2 = vRTALN(1 - X / L_{PW}) + (PA - F)X \tag{11}$$

$$V_{PS} = \sqrt{(2vRTA_P LN(1 - X / L_{PW}) + 2(PA_P - F)X / M_{PS}}$$

For the constants used, $X / LPW = .0736$ so the above simplified to

$$V_{PS} = \sqrt{2(PA - F)X / M_{PS}} \text{ or } X = M_{PS}V_{PS}^2 / (2(PA - F)) \tag{12}$$

After diaphragm bursts, the piston is being accelerated by pressure of the shockwave from the projectile and decelerated by friction forces and gas pressure between the piston and the water plug. When the water seal bursts, energy will be expanded to break the seal which decelerated the piston to zero. To calculate when the water seal burst, one calculates how far the piston travels to the point when the gas pressure in the region in between the piston and the seal reached its yield strength Y_D. If the water plug bursts before the piston is displaced x, the critical displacement can be calculated using the Ideal Gas Law $PV = vRT$.

$$Y_D = vRT / (A(L_{PW} - x_{crit}))$$

$$(AL_{PW} - x_{crit})) = vRT / Y_D \tag{13}$$

$$x_{crit} = L_{PW} - vRT / (Y_D A)$$

where ν equals the number of moles of air between the piston and water plug, T = temperature, A = the cross-section area of the front of piston, x_{crit} is the critical displacement of the piston when the water plug bursts, and L_{PW} = initial distance between piston and water plug.

Time/Displacement Offsetting of the Projectile and Piston

Time increments in the computer program are not calculated continuously; they are, in face only, calculated when the shockwave strikes a surface within the assembly; i.e., the surface of the projectile, diaphragm, piston, or water plug. When a barrier bursts, the computer program calculates, using a subroutine, when and where the projectile/piston is when the bursting occurs.

RESULTS OF COMPUTER SIMULATIONS

The computer simulations and data plots are shown in figure 4. There were few quantitative agreements with the results of the FORTRAN computer simulations and the experimental data. The results are, however, qualitatively similar to the point that there was a sharp spike in the pressure followed by a plateau outing.

The initial pressure on the projectile was calculated from the FORTRAN program (app A) to be 569,000 P, which was consistent with the value at point 2 on the data plot in figure 4. The initial pressure was determined to be instantaneous from the computer simulation; from the data plot from points 1 and 2, the plot shows a sharp pressure gradient 0.04 sec with noisy entries, which was the result of the projectile not entering the scat assembly before that time. In the computer simulation, the projectile pressure remains constant until the diaphragm bursts during which the shockwave pressure "spikes" upwards when the shockwave hits the back of the diaphragm. However, the data projectile pressure abruptly decreases after point 2 in figure 4 to one atmosphere, which was the projectile pressure before it entered the assembly. This could only have happened if the stiff coupler in figure 1 leaked out the pressure in the chamber in between the projectile and the stiff coupler. The diaphragm bursts at 0.2 sec in the data plot and 0.38 sec in the computer simulations. The difference was partially due to the effect of the stiff coupler in the scat assembly, which was not noted of the FORTRAN program. Differences of pressure maximum at points 3 and 4 in figure 4 were most likely due to the effects of turbulence, which the computer program didn't simulate. For both the data and computer simulation, the projectile pressure remained constant - indicating that the water plugs burst during the time after the shock reflected off the back of the piston and hit the projectile. The negative pressures are artifacts from the circuitry in the pressure sensor since negative pressures are not physically realistic. Most likely, they were offset incorrectly when the circuitry processed the data resulting in a negative pressure. Simulations predicted that the piston will decelerate to zero within the passably which was consistent with the experimental results.

The pressure in back of the shockwave is always greater than the pressure in front of the shockwave. In figure 4, the diaphragm bursts when the projectile pressure is just above the yield strength of the diaphragm in the simulation plot and about 36% below it in the case of the data plot. In both plots, the diaphragm could have only burst when the shockwave hit the back of the diaphragm. The large difference between the two plots in projectile pressure between the diaphragm burst may have been due the effect of turbulence in increasing pressure at surfaces during shockwave propagation. Different values of γ could explain the difference, but the same value of $\gamma = 1.4$ was used.

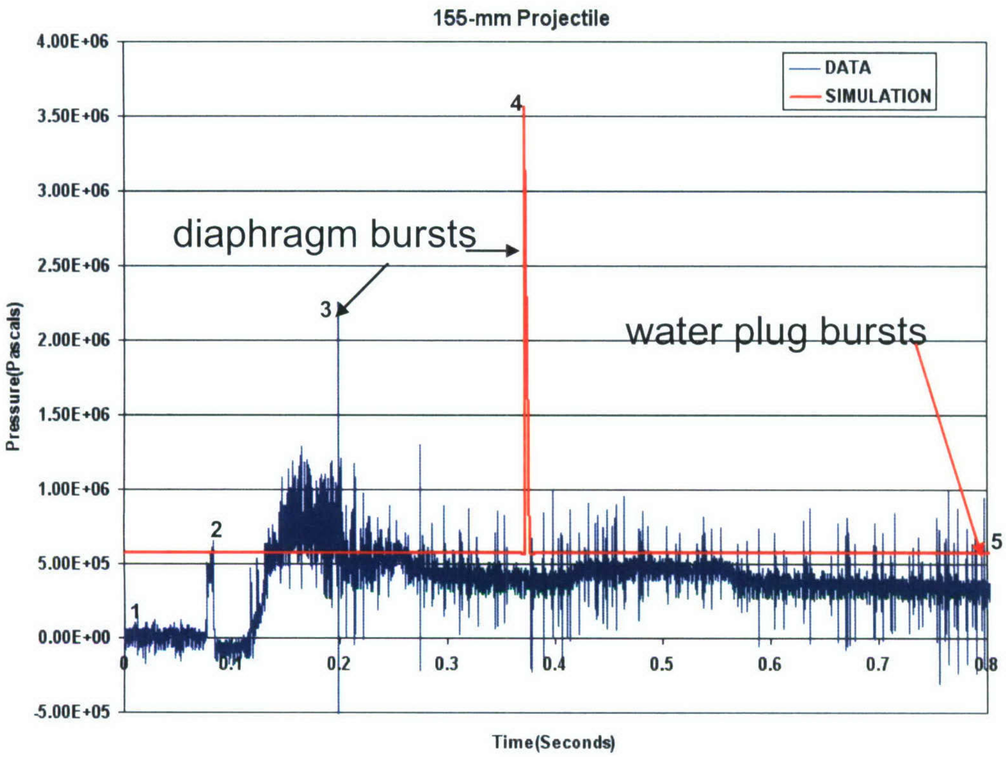


Figure 4
Projectile pressure versus time

CONCLUSIONS

The computer simulations matched the experimental data only in a qualitative sense to the point that there was a sharp spike in the projectile pressure when the diaphragm bursts, which instantaneously dropped to the initial projectile pressure until the water plug burst. The disparity between the two plots exists because the simulation failed to take into account the effects of turbulence on the generation of pressures throughout the assembly so there was not an exact quantitative concurrence between the simulations and data plots in terms of projectile pressure and the time coordinate when the diaphragm bursts. The simulations accurately predict a zero exit velocity for the piston.

REFERENCES

1. Birk, A., "A Novel Soft Recovery System for the 155-mm Projectile and Its Numerical Simulation," ARL-TR-2462, 4, 2001.

2. Anderson, J.D., Modern Compressible Flow, McGraw-Hill, 267.267, 2003.

3. Anderson, J.D., Modern Compressible Flow, McGraw-Hill, 696, 2003.

APPENDIX A
FORTRAN COMPUTER PROGRAM

A flowchart for the FORTRAN program used in this report is shown in figure A-1.

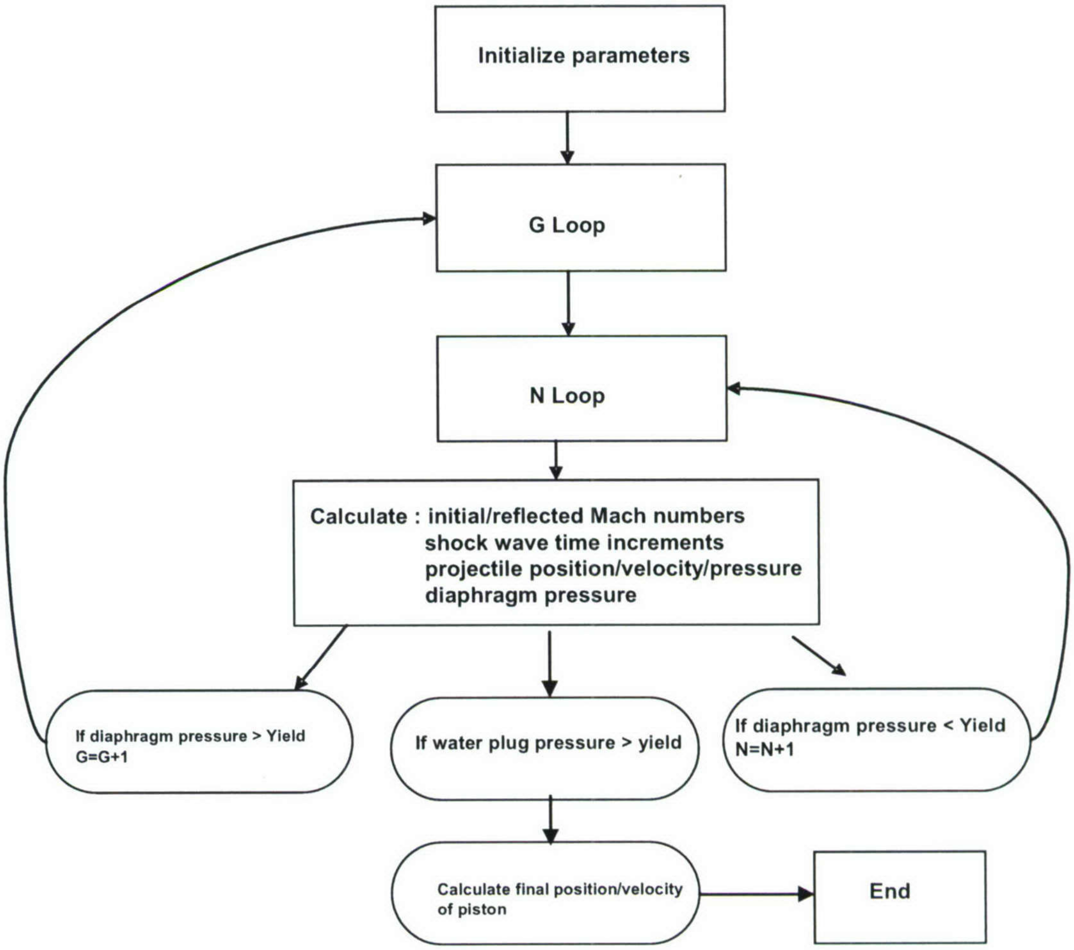


Figure A-1
Computer flowchart

```
PROGRAM SCAT

    !PROGRAMMER: KENNETH P. WALSH, PHD
    !DATE 08/10/2008
    !PORGRM CALCULTES THE PRESSURE ON THE FRONT OF A
    !PROJECTILE IN A SCAT GUN ASEMBLY

    INTEGER Z,N
    REAL PENETRATION,VO,VS,MASS,PENETRATION_OLD,B
    REAL P(100),DT(100),DX(100),MC(100),MR(100)
    REAL GAMMA,R,T(100),DTTOTAL,FACTOR,L,A,C,DP_OLD
    REAL VSOUND,TINIT,VINIT,DELTA_V,NU,RATIO,VP_OLD
    REAL YIELD,AREA,V(100),DTTOTAL_OLD,A1,B1,C1
    CHARACTER*8 FILENAME

    !INITIALIZE PHYSICAL PARAMETERS

    YIELD = 3447378 !YIELD STRENGTH OF DIAPHRAGM
    MU_ST_STEEL = .74
    MU_KN_STEEL = .57
    NU=.0411
    MP = 5.01
    MASS=45.6  !MASS OF PROJECTILE
    ATM=101325 !ATMOSPHERIC PRESSURE
    P(1)=ATM
    DIA_THICKNESS = .002 !DIAPHRAGM THICKNESS
    LPW=24.4 !DISTANCE FROM PISTON TO WATER PLUG
    AREA= .0189 !CORSS SECTION AREA OF PISTON AND PROJECTILE
    R=289
    T(1)=300
    GAMMA=1.4

    VP_OLD = 0
    DP_OLD = 0

 55   FORMAT(E16.7,E16.6)

    PRINT *,'ENTER NUMBER OF SECTIONS'
    READ *,GFINAL
```

```
!G CHANES WHEN DIAPHRAM BURST
!N CHANGES AS SHOCKWAVE TRAVELS FROM ONE SURFACE TO
ANOTHER

DO 100 G=1,GFINAL,1
   IF(G.EQ.1)THEN
     PRINT *,'ENTER FILENAME'
     READ *, FILENAME
     OPEN(UNIT=1,FILE=FILENAME,STATUS='NEW')

     PRINT *,'ENTER INTIAL PROJECTILE VELOCITY'
     READ *,VO
     V(1) = VO
     TINIT = 0
     IF(P(1).GT.YIELD)THEN

      GFINAL = GFINAL +1

    ENDIF

   ENDIF

IF(G.EQ.2)THEN

DELTA_V  = SQRT(2*YIELD*AREA*DIA_THICKNESS/MP)

  TINIT_OLD = TINIT

ENDIF

PRINT *,'ENTER LENGTH OF SECTION'
READ *,L

N=1
Z=1
!PENETRATION = HOW FAR PROJECTLE IS DISPLACED
PENETRATION_OLD =0
PENETRATION=0
DTTOTAL_OLD=DTTOTAL

!CALCULATE VELOCITY OF SOUN

VSOUND=SQRT(GAMMA*R*T(1))
```

```
DO WHILE(N.LT.100)
NOLD=N

IF(N.EQ.1)THEN

!CALCULATE INITIAL MACH NUMBER

   A1=1
   B1=-2 - (GAMMA+1)*V(N)*V(N)*GAMMA/(2*VSOUND*VSOUND)
   C1=1-(GAMMA-1)*V(N)*V(N)*GAMMA/(2*VSOUND*VSOUND)
   RATIO=(1/(2*A1))*(-B1-SQRT(B1*B1-4*A1*C1))
   MR(N) = SQRT((GAMMA+1)*(RATIO-1)/(2*GAMMA) +1)
   TOTO1= MR(N)/(MR(N)*MR(N)-1)
   TOTO2=(1+2*(GAMMA-1))*(MR(N)*MR(N)-1)
   TOTO3= (GAMMA+1/(MR(N)*MR(N)))/((GAMMA+1)*(GAMMA+1))

  IF(-B1.GT.SQRT(B1*B1-4*A1*C1))THEN

    IF(MR(N).GT.1)THEN

    MC(N)=(TOTO1)*SQRT(TOTO2*TOTO3)
    MR(N+1)= .5*(1+SQRT(1+ 4*MC(N)))

    ENDIF

    IF(MR(N).LE.1)THEN

    RATIO=(1/(2*A1))*(-B1+SQRT(B1*B1-4*A1*C1))
    MR(N) = SQRT((GAMMA+1)*(RATIO-1)/(2*GAMMA) +1)
    TOTO1= MR(N)/(MR(N)*MR(N)-1)
    TOTO2=(1+2*(GAMMA-1))*(MR(N)*MR(N)-1)
    TOTO3= (GAMMA+1/(MR(N)*MR(N)))/((GAMMA+1)*(GAMMA+1))
    MC(N)=(TOTO1)*SQRT(TOTO2*TOTO3)
    MR(N+1)= .5*(1+SQRT(1+ 4*MC(N)))

    ENDIF

   ENDIF

  IF(-B1.LT.SQRT(B1*B1-4*A1*C1))THEN

     MC(N)=(TOTO1)*SQRT(TOTO2*TOTO3)
     MR(N+1)= .5*(1+SQRT(1+ 4*MC(N)))
```

```
  ENDIF

   VS=MR(N)*VSOUND
   P(2*N)=P(Z)*(GAMMA+1+2*GAMMA*(MR(Z)*MR(Z)-1))/(GAMMA+1)

   IF(G.LT.2)THEN

   WRITE(1,55)TINIT,P(2*N)
   ENDIF
   RATIO=(GAMMA+1+2*GAMMA*SQRT(MR(N+1)*MR(N+1)-1))/(GAMMA+1)
   R1=((GAMMA+1)/(GAMMA-1)+RATIO)/(1+(GAMMA+1)*RATIO/(GAMMA-1))
   ALPHA=RATIO*R1
   T(2*N)= ALPHA*T(2*N-1)

ENDIF

IF(N.GT.1)THEN

!CALCULATE REFLECTION MACH NUMBER

  TOTO1= MR(Z-1)/(MR(Z-1)*MR(Z-1)-1)
  TOTO2=(1+2*(GAMMA-1))*(MR(Z-1)*MR(Z-1)-1)
  TOTO3= (GAMMA+1/(MR(Z-1)*MR(Z-1)))/((GAMMA+1)*(GAMMA+1))
  MC(Z-1)=(TOTO1)*SQRT(TOTO2*TOTO3)
  MR(Z)= .5*(1+SQRT(1+ 4*MC(Z-1)))
  PRINT *,'MR(Z),MC(Z-1),MR(Z+1)'
  PRINT *,MR(Z-1),MC(Z-1),MR(Z)
  PRINT *,'ENTER FACTOR TO CALCULATE  NEWPRESSURE'
  READ *, FACTOR
  P(2*N)=P(2*N-1)*FACTOR
  CALL  SOUNDSPEED1(MR,N,T,VSOUND)
  VS=VSOUND*MR(Z)

 ENDIF

 IF(N.EQ.1)THEN

  DT(Z)= (L-PENETRATION)/VS + TINIT_OLD

 ELSEIF(N.GT.1)THEN

  DT(Z)= (L-PENETRATION)/VS
```

```
 ENDI
DX1=V(Z)*(L-PENETRATION)/VS
DX2=-P(2*N)*AREA*(L-PENETRATION)*(L-PENETRATION)/(2*MASS*VS*VS)

!CALCULATE DISPLACEMENT OF PROJECTILE AS SHOCKWAVE MOVES LEFT
TO RIGHT

DX(Z) = DX1 + DX2

 PENETRATION = PENETRATION_OLD + DX(Z)

IF(G.EQ.2.AND.N.GE.2)THEN

 PRINT *,'G.EQ.2.AND.N.GE.2'

 !CALCULATE POSITION OF PISTON WHEN WATER PLUG BURSTS

  CALL PSHIFT2(DCRIT,P,N,VP,DP,VP_OLD,DP_OLD,DT,Z,TC,DP

      IF(DP.GE.DCRIT)THEN

      L = L +  DCRIT

      PRINT *,'WATER PLUID HAS BURST'

      VINIT = V(Z)
      TINIT= DTTOTAL_OLD + TC + TINIT_OLD
      WRITE(1,55)TINIT,P(2*N)
      CALL PISTON2(N,P,VP,LPW,XCRIT)
      GO TO 100

     ELSEIF(DP.LT.DCRIT)THEN

      PENETRATION = PENETRATION - DPP

     ENDIF

 ENDIF

   PENETRATION_OLD=PENETRATION
17  FORMAT(1X,'DX(',I2,')=',E10.4)

V(Z+1)=V(Z)- P(2*N)*AREA*DT(Z)/MASS
```

```
51    FORMAT(1X,'V(',I2,')= ',E10.4)

      IF(N.GE.2)THEN

      !CALCULATE REFLECTIVE MACH NUMBER

        TOTO1= MR(Z)/(MR(Z)*MR(Z)-1)
        TOTO2=(1+2*(GAMMA-1))*(MR(Z)*MR(Z)-1)
        TOTO3= (GAMMA+1/(MR(Z)*MR(Z)))/((GAMMA+1)*(GAMMA+1))

        MC(Z)=(TOTO1)*SQRT(TOTO2*TOTO3)
        MR(Z+1)= .5*(1+SQRT(1+ 4*MC(Z)))

          PRINT *,'MR(Z),MC(Z),MR(Z+1)'
          PRINT *,MR(Z),MC(Z),MR(Z+1)
          PRINT *,'ENTER FACTOR TO CALCULATE  NEWPRESSURE'
          READ *, FACTOR
          P(2*N+1)=P(2*N)*FACTOR

         IF(P(2*N+1).GT.YIELD.AND.G.EQ.1) THEN

  !CALCULATE POSITION OF PROJECTLE WHEN DIAPHRAGM BURSTS

        CALL XTSHIFT1C(TFINAL,DT,DX,L,V,P,N,Z)
        PRINT *,'THERE IS TOO NUCH PRESSURE!'
        PRINT 300,L-PENETRATION

          VINIT=V(Z+1)
          TINIT=DTTOTAL_OLD + TFINAL
          WRITE(1,55)TINIT,P(2*N)
          GO TO 100

         ENDIF

 !CALCULATE SPEED OF SOUND WHEN SHOCKWAVE TRAVELS RIGHT TO
LEFT

         CALL  SOUNDSPEED2(MR,N,T,VSOUND)

        VS=VSOUND*MR(Z+1)
```

```
      ENDIF

      IF(N.EQ.1)THEN

      !CALCULATE PRESSURE IN BACK OF SHOCKWAVE

         PRINT *,'MR(Z),MC(Z),MR(Z+1)'
         PRINT *,MR(Z),MC(Z),MR(Z+1)
         PRINT *,'ENTER FACTOR TO CALCULATE  NEWPRESSURE'

          READ *, FACTOR
          P(2*N+1)=P(2*N)*FACTOR

         IF(P(2*N+1).GT.YIELD.AND.G.EQ.1) THEN

         PRINT *,'THERE IS TOO NUCH PRESSURE!'
300        FORMAT(1X,'ADD ',E19.4,1X,'TO THE NEXT SECTION')
         PRINT 300,L-PENETRATION

    !CALCULATE POSITION OF PROJECTILE WHEN DIAPHRAGM BURSTS

         CALL XTSHIFT1C(TFINAL,DT,DX,L,V,P,N,Z)
         VINIT = V(Z+1)
         TINT=DTTOTAL_OLD + TFINAL
         WRITE(1,55)TINIT,P(2*N)
         PRINT *,'DTTOTAL_OLD,DT(Z)'
         PRINT *,DTTOTAL_OLD,DT(Z)
         GO TO 100

         ENDIF

       CALL  SOUNDSPEED2(MR,N,T,VSOUND)

       VS=VSOUND*MR(Z+1)

     ENDIF

     PRINT *,'AREA,MASS.MR(Z+1),VS,VSOUND'
     PRINT *,AREA,MASS,MR(Z+1),VS,VSOUN
```

!CALCULATEDISPLACEMENT OF PROJECTILE WHEN SHOCKWAVE MOVES RIGHT TO LEFT

```
A=P(2*N)*AREA/(2*MASS*VS*VS)
B1=(MASS*VS*VS)
B=1+V(Z)/VS -P(2*N)*AREA*(L-PENETRATION)/B1
C=-V(Z)*(L-PENETRATION)/VS +P(2*N)*AREA*(L-PENETRATION
&)*(L-PENETRATION)/(2*MASS*VS*VS)
DX(Z+1) = (1/(2*A))*(-B+SQRT(B*B-4*A*C))


PRINT *,'A,B,C,DX(Z+1)'
PRINT *,A,B,C,DX(Z+1)

PENETRATION = PENETRATION_OLD + DX(Z+1)
VINIT=V(Z+1)
DT(Z+1)= (L - PENETRATION)/VS

IF(G.EQ.2)THEN

!CALCUALTE POSITION OF PISTON WHEN WATER PLUG BURSTS

 CALL PSHIFT(DCRIT,P,N,VP,DP,VP_OLD,DP_OLD,DT,Z,TC,DPP)
 PRINT *,'PSHIFT'

      IF(DP.GE.DCRIT)THEN

      L = L +  DCRIT

      PRINT *,'WATER PLUID HAS BURST'

      VINIT = V(Z+1)
      TINIT= DTTOTAL_OLD + TC + TINIT_OLD
      PRINT *,'DTTOTAL_OLD,TINIT_OLD,TC'
      PRINT *,DTTOTAL_OLD,TINIT_OLD,TC
      WRITE(1,55)TINIT,P(2*N)
      CALL PISTON1(N,P,VP,LPW,XCRIT)
      GO TO 100

     ELSEIF(DP.LT.DCRIT)THEN

      PENETRATION = PENETRATION - DPP

     ENDIF
```

```
      ENDIF
       DTTOTAL= DT(Z+1) + DT(Z) + DTTOTAL_OLD
       DTTOTAL_OLD = DTTOTAL
       WRITE(1,55)DTTOTAL,P(2*N)
       PRINT *,'DTTOTAL,P(2*N)'
       PRINT *,DTTOTAL,P(2*N)

       V(Z+2)=V(Z+1)- P(2*N)*AREA*DT(Z+1)/MASS
2     FORMAT(1X,'TIME SHOCKWAVE #',I2,1X,'HITS PROJECTILE =',E10.2)
3     FORMAT(1X,'PRESSURE OF SHOCKWAVE # ',I2,'= ',E10.2)

      PRINT *,'Z,DTTOTAL,PENETRATION,N,P(2*N),V(Z+1)'
      PRINT *, Z,DTTOTAL,PENETRATION,N,P(2*N),V(Z+1)

       PENETRATION_OLD=PENETRATION

       Z = Z + 2
       N = N + 1

       PRINT *,'SHOCKWAVE VELOCITY ='
       PRINT *,VS

       ENDDO

100    CONTINUE

        END

      SUBROUTINE SOUNDSPEED1(MR,N,T,VSOUND)

      INTEGER N
      REAL RATIO,GAMMA,ALPHA,MR(100),T(100)
      REAL VSOUND,R1

       R=289
       GAMMA =1.4

       RATIO=(GAMMA + 1 + 2*GAMMA*SQRT(MR(N+1)*MR(N+1)-1))/(GAMMA+1)
       R1=((GAMMA+1)/(GAMMA-1)+RATIO)/(1+(GAMMA+1)*RATIO/(GAMMA-1))
       ALPHA=RATIO*R1

       T(2*N)= ALPHA*T(2*N-1)
```

```
VSOUND = SQRT(GAMMA*R*T(2*N-1))
RETURN
END


SUBROUTINE SOUNDSPEED2(MR,N,T,VSOUND)

REAL RATIO,GAMMA,ALPHA,MR(100),T(100)

 R=289
GAMMA =1.4

RATIO = (GAMMA + 1 + 2*GAMMA*SQRT(MR(N+1)*MR(N+1)-1))/(GAMMA+1)

ALPHA=RATIO*((GAMMA+1)/(GAMMA-
1)+RATIO)/(1+(GAMMA+1)*RATIO/(GAMM
&A-1))

T(2*N+1)= ALPHA*T(2*N)

VSOUND= SQRT(GAMMA*R*T(2*N+1))

RETURN
END

SUBROUTINE XTSHIFT1A(TFINAL,DT,PENETRATION_OLD,L,V,P,N,Z)


INTEGER Z,N
REAL Z1,Z2,Z3,PENETRATION_OLD,TFINAL,MASS,AREA
REAL V(100),P(100),DT(100),F, MU_KN_STEEL

 MASS=45.26
 AREA=.0189
 MU_KN_STEEL = .57
 F=9.8*MASS*MU_KN_STEEL

PRINT *,'SHIFT IT 1A'

Z1=(P(2*N)*AREA+F)/MASS
Z3=L - PENETRATION_OLD
Z2=-V(Z)

 TFINAL=(-Z2+SQRT(Z2*Z2-4*Z1*Z3))/(2*Z1)
```

```
RETURN

END

SUBROUTINE XTSHIFT1B(TFINAL,DT,PENETRATION_OLD,L,V,P,N,Z)

INTEGER Z
REAL Z1,Z2,Z3,PENETRATION_OLD,TFINAL,MASS,AREA,L
REAL V(100),P(100),DT(100),MU_KN_STEEL

 MASS=45.26
 AREA=.0189
 MU_KN_STEEL = .57
 F=9.8*MASS*MU_KN_STEEL

PRINT *,'SHIFT IT 1B'

Z1=(P(2*N)*AREA+F)/(2*MASS)
Z3=L - PENETRATION_OLD
Z2=-V(Z)

PRINT *,'Z2*Z2-4*Z1*Z3'
PRINT *, Z2*Z2-4*Z1*Z3

  TFINAL=(-Z2+SQRT(Z2*Z2-4*Z1*Z3))/(2*Z1)
 RETURN
 END

SUBROUTINE XTSHIFT2(TFINAL,PENETRATION_OLD,L,V,P,N,Z)

INTEGER Z,N
REAL Z1,Z2,Z3,PENETRATION_OLD,L,MASS,AREA
REAL V(100),P(100),TFINAL,MU_KN_STEEL

 MASS=45.26
 AREA=.0189
 MU_KN_STEEL = .57
 F=9.8*MASS*MU_KN_STEEL

Z1=(P(2*N)*AREA+F)/(2*MASS)
Z3=L - PENETRATION_OLD
Z2=-V(Z+1)
PRINT *,Z1,Z2,Z3
TFINAL=(-Z2+SQRT(Z2*Z2-4*Z1*Z3))/(2*Z1)
```

```
RETURN

 END

SUBROUTINE XTSHIFT1C(TFINAL,DT,DX,L,V,P,N,Z)

INTEGER Z,N
REAL Z1,Z2,Z3,TFINAL,MASS,AREA, MU_KN_STEEL
REAL V(100),P(100),DT(100),DX(100)

MASS=45.26
AREA=.0189
 MU_KN_STEEL = .57
 F=9.8*MASS*MU_KN_STEEL
PRINT *,'SHIFT IT 1C'

Z1=(P(2*N)*AREA+F)/MASS
Z3= DX(Z)
Z2=-V(Z)

 TFINAL=(-Z2+SQRT(Z2*Z2-4*Z1*Z3))/(2*Z1)

 RETURN

 END


SUBROUTINE PISTON1(N,P,VP,LPW,XCRIT)

  INTEGER N
  REAL P(100),YIELD, DELTA_V,VFINAL
  REAL PISTONMASS,WATERMASS, L,MU_KN_STEEL,FWORK
  REAL VP,LPW,XCRIT

      PISTONMASS = 5.01
      WATERMASS = 100
      AREA = .0189
      L=.002
      YIELD = 3447378
      MU_KN_STEEL = .57
      F=9.8*PISTONMASS*MU_KN_STEEL
      FWORK= (P(2*N+1)*AREA -F)* (LPW-XCRIT + 24.4)
      DELTA_V  =SQRT(2*FWORK/PISTONMASS)
      VFINAL = VP - DELTA_V
```

```
      IF(VFINAL.GT.0)THEN

      PRINT *,'FINAL PISTON VELOCITY IS'

       PRINT *, VFINAL

      ENDIF

      IF(VFINAL.LE.0)THEN

      PRINT *,'PISTON WILL STOP AT'
      PRINT *, 24.4 + (LPW-XCRIT) -PISTONMASS*VP*VP/(2*(P(2*
     &N+1)*AREA -F))
      PRINT *,'METERS FROM END OF SCAT'

      ENDIF

      RETURN

      END

      SUBROUTINE PSHIFT(DCRIT,P,N,VP,DP,VP_OLD,DP_OLD,DT,Z,TC,DPP)

      INTEGER N,Z
      REAL YIELD,MU_KN_STEEL,NU,MP,DCRIT,P(100)
      REAL AREA,LPW,T,F,A,TC,A1,A2,A3,DP_OLD,VP_OLD
      REAL DPP,VP,DP,DT(100)

      MP = 5.01
      LPW=24.4
      AREA= .0189
      YIELD = 3447378
      MU_KN_STEEL = .57
      NU=.0411
      T=300
      R=289
      DCRIT = LPW - NU*R*T/(YIELD*AREA)
      A=(P(2*N+1)*AREA - F)/MP
      VP = VP_OLD + A*DT(Z+1)
      DP= DP_OLD + VP_OLD*DT(Z) + A*DT(Z)*DT(Z)/2
      DPP= VP_OLD*DT(Z) + A*DT(Z)*DT(Z)/2
      A1 = A/2
      A2 = VP_OLD
```

```
      A3 = -DPP
      TC = (-A2+SQRT(A2**2-4*A1*A3))/(2*A1)
      PRINT *,'TC'
      PRINT *,TC
      DP_OLD = DP
      VP_OLD = VP

      RETURN

      END

SUBROUTINE PSHIFT2(DCRIT,P,N,VP,DP,VP_OLD,DP_OLD,DT,Z,TC,DPP)

      INTEGER N,Z
      REAL YIELD,MU_KN_STEEL,NU,MP,DCRIT,P(100)
      REAL AREA,LPW,T,F,A,TC,A1,A2,A3,DP_OLD,VP_OLD
      REAL DPP,VP,DP,DT(100)
      MP = 5.01
      LPW=24.4
      AREA= .0189
      YIELD = 3447378
      MU_KN_STEEL = .57
      NU=.0411
      T=300
      R=289
      DCRIT = LPW - NU*R*T/(YIELD*AREA)

      A=(P(2*(N-1)+1)*AREA - F)/MP
      VP = VP_OLD + A*DT(Z+1)
      DP= DP_OLD + VP_OLD*DT(Z+1) + A*DT(Z+1)*DT(Z+1)/2
      DPP= VP_OLD*DT(Z+1) + A*DT(Z+1)*DT(Z+1)/2
      A1 = A/2
      A2 = VP_OLD
      A3 = -DPP

      TC = (-A2+SQRT(A2**2-4*A1*A3))/(2*A1)
      DP_OLD = DP
      VP_OLD = VP
      PRINT *,'TC'
      PRINT *,TC

      RETURN
      END
```

```
SUBROUTINE PISTON2(N,P,VP,LPW,XCRIT)

INTEGER N
REAL P(100),YIELD, DELTA_V,VFINAL
REAL PISTONMASS,WATERMASS, L,MU_KN_STEEL,FWORK
REAL VP,LPW,XCRIT

   PISTONMASS = 5.01
   WATERMASS = 100
   AREA = .0189
   L=.002
   YIELD = 3447378
   MU_KN_STEEL = .57
   F=9.8*PISTONMASS*MU_KN_STEEL

   FWORK=(P(2*(N-1)+1)*AREA -F)* (LPW-XCRIT + 24.4)

   DELTA_V  =SQRT(2*FWORK/PISTONMASS)
   VFINAL = VP - DELTA_V
   PRINT *,'VFINAL ='
   PRINT *,VFINAL

  IF(VFINAL.GT.0)THEN

  PRINT *,'FINAL PISTON VELOCITY IS'

   PRINT *, VFINAL

  ENDIF

  IF(VFINAL.LE.0)THEN

  PRINT *,'PISTON WILL STOP AT'
  PRINT *,'PISTON WILL STOP AT'
  PRINT *, 24.4 + (LPW-XCRIT) -PISTONMASS*VP*VP/(2*(P(2*
&N+1)*AREA -F))
  PRINT *,'METERS FROM END OF SCAT'

  ENDIF
  RETURN

  END
```

GLOSSARY

$\Delta\tau_N$	Time shockwave takes for its nth transversal along the tube
L	Initial distance between projectile and diaphragm or piston
M_{NR}	Mach number of shockwave after the nth reflection
V_S	Velocity of sound in tube
Δx_N	Displacement of projectile during the nth transversal of the shockwave along the tube
Δx_{crit}	Displacement of piston where water plug bursts
M_{IC}	Constant used to determine the Mach number after the nth reflection of shockwave
V_P	Particle velocity
M_{INT}	Mach number before shockwave is reflected off of a surface
T_2	Temperature in back of shockwave before shockwave first hits back of diaphragm
T_1	Temperature in front of shockwave before shockwave first hits back of diaphragm
V_1	Sound speed at temperature T_1
u	Particle velocity
M_P	Mass of projectile
L_{PW}	Initial distance between piston and water plug
P	Pressure exerted on back of piston by shockwave
F	Friction force
V_P	Velocity of projectile
V_{PS}	Velocity of piston
X	Displacement

Y_D	Yield pressure of diaphragm and water plugs
$v(x_N)$	Projectile velocity after nth reflection/creation of shockwave on the surface of the projectile
$v(x_N)$	Projectile velocity after nth reflection of shockwave on the surface of the piston/diaphragm
A_{PS}	Piston acceleration
M_{PS}	Piston mass
A	Cross-section area of projectile and piston
t	Time
M_{BNR}	nth backward reflected Mach number
V_{Si}	Speed of sound in region with temperature
T_i	Projectile pressure in front of the shockwave

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